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Mechanism of positive spark discharges with long gaps in air at atmospheric pressure

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With 25 figures in the text

1. Introduction

The problem of the development of spark discharge in gases has long been discussed to a great extent. Information on the extensive literature on the subject is to be found in many summarizing works, e.g. (1, 2). Although many important additions to the classical Townsend theory have been given, particularly during the last years, also the new streamer theory [first modification by Loeb and Meek (1), second modification by Raether (2)] is applicable only to a limited extent. As far as small $p\,\delta$ values (p—pressure, δ—gap length) are concerned—for the Townsend theory up to $p\,\delta = 200$–$1\,000$, for the streamer theory up to $\delta\,p = 10\,000$ mm Hg. cm—the experimental and theoretical conditions generally accord well, but for higher $p\,\delta$ values this is by no means the case. The difference between the experiments and the theory are here highly increased, particularly in non-homogeneous fields. Much is doubtful and requires experimental corroboration, these problems evidently being particularly difficult to clear up. This gives rise to certain doubts as to the validity of the streamer theory for high pδ values and highly non-homogeneous fields. In air at atmospheric pressure, this implies that the mechanism of spark discharge in gaps longer than 15 cm cannot be considered fully clear as yet. Particularly in the case of long gaps, however, the problem of the development of spark discharge is of great practical importance: it will suffice to mention e.g. lightning research, the corona phenomenon, and the question of the dielectric strength in high-voltage engineering. In order to remedy the lack of sufficient experimental material, experiments have been carried on at the Institute of High Tension Research, University of Uppsala, for the purpose of investigating photographically the development of the mechanism of spark discharge in air at atmospheric pressure with long gaps.

The experiments described in the following are part of a research program of the Institute for the purpose of investigating to what extent the streamer theory is applicable on long gaps. As it is known that each electrode has a separate streamer process and it has not yet been established how the region of discharge of one electrode influences that of the other electrode, it was found suitable to use the arrangement sphere-to-plane, where only one region of discharge (sphere electrode) was required. Thus we hoped to obtain a pure picture of the mechanism of positive discharge.

All the following experiments were performed with *positive* polarity, which should be emphasized particularly, as the influence of the polarity on the properties of the discharge is of great importance.

2. Apparatus and technique

The spark gap was constituted by an extended (2 × 2 m) plane electrode, which was constantly connected to earth, and a point electrode (cone of 30°) or sphere electrode (diameter of 1.44–3.2–6.2–15–25–50 cm), which was exposed to impulse voltage of standard wave (1/50 μs). Special importance was attached to long gaps: the highest value was 155 cm, whereas gap lengths under 5 cm were not used in the experiments.

The pre-discharge emits very little visible light, and it must therefore be observed and photographed in a dark room. All the experiments were consequently performed in darkness at atmospheric pressure (humidity 50–60 %) without ultraviolet illumination of the spark gap. The spark gap was carefully protected from illumination from other spark gaps employed in the neighbourhood, i.e. the process of spark discharge was the natural one. The surface of the sphere was carefully cleaned with trichlorethylene before each series of measurements.

The photographs of the separate phases of development of the spark discharge were taken with the chopping method (3, 4, 5). The chopping gap was placed parallel to the spark gap and adjusted so as to start operating at the desired space of time before the discharge in the spark gap and so as to cut off the voltage impulse at the right moment. Only the desired stages of the discharge, photographed with a camera with a quartz rocksalt lens system ($F = 1:5$, $f = 18$ cm), were recorded.

3. Potential curves for the arrangement sphere-to-plane

The potential curve is of good use in order to get a general survey of the process of spark discharge at the various gap lengths. Preliminary conclusions may be drawn from the curve as to whether the mechanism remains unchanged or whether a change is to be assumed with increasing gap length. The general character of the potential curve—the dependance on the length of the gap—is well known (1, 6, 7, 8, 9). Mostly, however, the measurements referred to symmetric arrangements or comparatively short gaps. Extensive control and supplementary investigation with reference to long gaps and high voltage are necessary for all the electrodes concerned.

The presence of ions and electrons in the spark gap is purely accidental, and the separate discharges take place altogether independently of each other. If a number of discharge tests are carried out under similar conditions, discharge phenomena (spark-over or corona) are not had with every impulse. Many impulses are not accompanied by discharge phenomena. The percentage of discharges may be recorded, but it is not invariable, being subject to a certain spreading. In the following measurements it was consequently necessary to define the corona voltage and the breakdown voltage more closely.

In the following, corona voltage means the voltage at which a light phenomenon is observed at the electrodes in only one out of 30–35 impulses (about 3 %). This value is of course somewhat too high in relation to the limit value of the corona

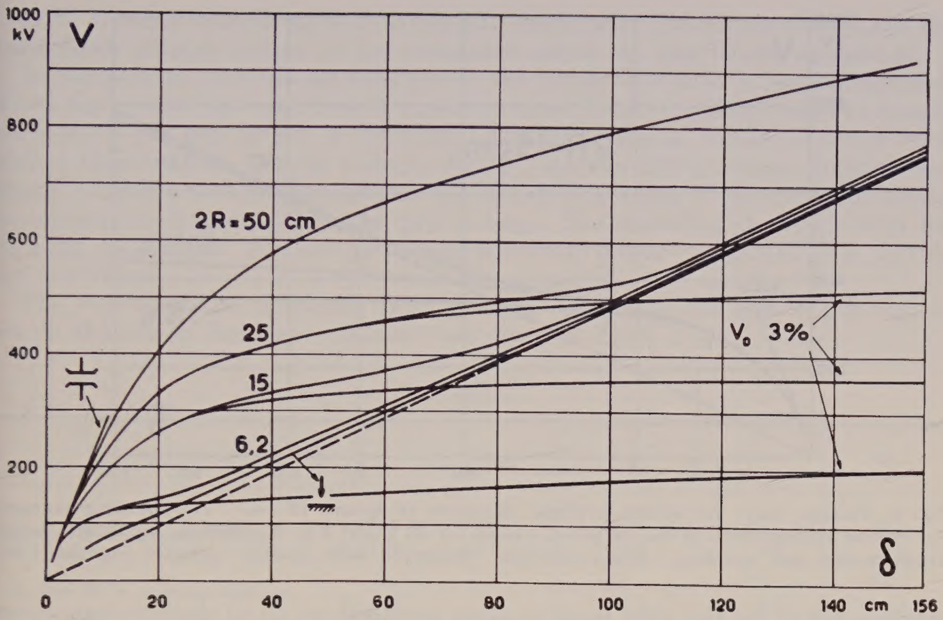

Fig. 1. Sparking and 3 % corona voltage from spheres and point towards a plate at 760 mm Hg and 20° C, as a function of the gap length with the diameter of the sphere as parameter, measured at positive impulse 1/50 μs.

voltage, at which the percentage of light phenomena should be considerably lower. Practical considerations, however, made it necessary to operate with the less time-consuming 3 % corona voltage. By way of comparison, the 50 % corona voltage was measured as well, i.e. the voltage producing 15 light phenomena in 30 impulses. Correspondingly, 50 % breakdown voltage (or simply breakdown voltage) is the voltage producing breakdown in the spark gap in half the number of 30 impulses with undisturbed discharge process (the full tension wave operates in the spark gap).

The voltage was measured by a sphere gap inserted parallel to the test gap and reduced to normal temperature and atmospheric pressure (20° C, 760 mm Hg). The corona and breakdown voltage curves are reproduced in Fig. 1, which by way of comparison also gives the breakdown voltage with plane-to-plane electrodes (10, 11).

A more detailed analysis of the curves reveals that the well-known characteristics of the symmetric arrangement sphere-to-sphere are valid also for the unsymmetrical arrangement sphere-to-plane used here. The main characteristics of the process are recorded schematically in Fig. 2 by the corona and breakdown voltage curves. With short gaps (a), the field growing ever more homogeneous, the curves coincide with the plane-to plane curve for all sizes of electrodes. With longer gaps, the sparking curve first rises steeply (a–b), then flatly (b–c), and from a certain point (c) more steeply again. At the end of this stretch (c–d), the curve changes into a straight line, which runs parallel with another straight line (running through zero). With long gaps, the curves for the point-to-plane arrangement coincide with the latter straight line. We propose to regard the straight line through the zero-point as the

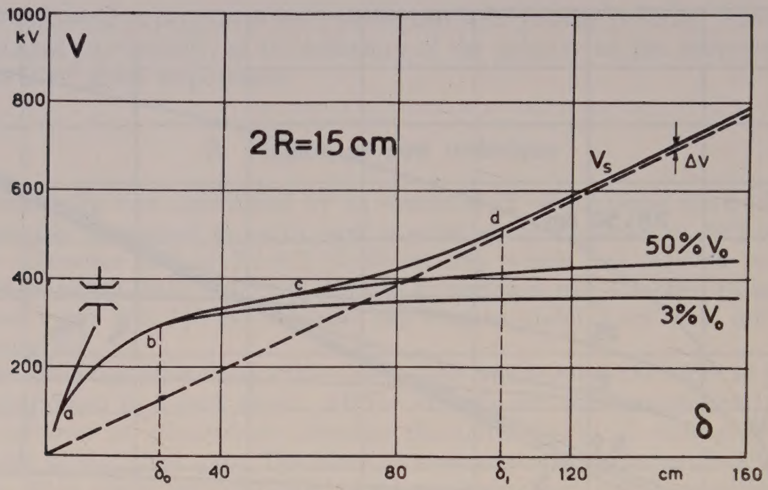

Fig. 2. Voltage curve for sphere-to-plane (diameter of sphere 15 cm). V_S—sparking voltage. For corona voltage two curves are given: values for 50 % and 3 %. δ_0—critical gap length, below which corona and sparking voltage coincide. Measured with positive polarity impulse 1/50.

sparking curve for the ideal point-to-plane arrangement (ideal characteristic curve of point). This gives us the definition of the ideal point. The point used (a brass rod of 8 mm diameter, cone of 30°) gives a curve which deviates from the ideal characteristic curve (Fig. 1)—more if the gaps are short, whereas the difference grows smaller with increasing gap length, the two curves finally coinciding at a gap length of 90 cm.

The $dV/d\delta$ value of the sparking curve is thus first slightly declining, then steeply declining, and finally constant. This fact deserves special attention: it proves that the mechanism of the development of discharge probably does not remain constant with increasing gap length (δ). A uniform discharge process, independent of the form and size of the electrodes, may however be assumed in the rectilinear part of the curve (high δ value). Here the curves run closely together, each of them changing into a straight line, which runs parallel with the ideal characteristic curve of point at the distance ΔV and assumes the same $dV/d\delta$ value, viz. 4.82 kV/cm. As is seen from table 1, the distance (ΔV) between the characteristic curve of sphere and the ideal characteristic curve of point increases with the diameter of the sphere.

Table 1.

Diameter of sphere (2 R) cm	6.2	15	25
ΔV . . . . kV	4	13	22
$\Delta V/2R$	0.64	0.87	0.88

The precision of the determination of ΔV from the curves should not be overestimated, but ΔV does seem to increase somewhat in proportion to the diameter of the sphere.

Both voltages coincide up to a certain gap length (δ_0). The corona voltage and the breakdown voltage cannot be kept separate unless the gap length exceeds δ_0.

In comparison with the sparking curve, the curve for corona is less complicated. From the critical gap length on, it runs ever more flatly. Its value seems to remain constant if the gap length is sufficient. The 50 % corona voltage is about 20 % higher than the 3 % corona voltage (Fig. 2). As the 100 % corona voltage very nearly coincides with the breakdown voltage, the spreading of the curve for corona is comparatively great when the gap is long. The spreading decreases with decreasing gap length. The corona voltage is however not to be regarded as a sharply defined value.

The results of the measuring (Fig. 1) of δ_0, $\delta_0/2$ R and the gap length (δ_1), at which the curves become rectilinear, are given in Table 2.

Table 2.

Diameter of sphere cm		Point	6.2	15	25
δ_0 for 3 % corona voltage	cm	—	12	25	50
	$\delta_0/2\,R$	—	1.8	1.7	2.0
δ_0 for 50 % corona voltage	cm	—	20	52	100
	$\delta_0/2\,R$	—	3.2	3.5	4.0
Gap length (δ_1) at which the curve becomes rectilinear	cm	90	100	100	110

4. Photographs of spark discharge

a. General description.

The process of spark discharge in air at atmospheric pressure in a non-homogeneous field has not been much investigated experimentally in its details. The onset stages of the preliminary phenomena leading to the breakdown in long gaps have so far—with the exception of a few experimental investigations—almost exclusively been the object of theoretical speculation. It is however undeniable that knowledge of the pre-processes is of special interest for the further development of the theory. Our main object has therefore been to record the pre-processes—in so far as they are accompanied by emission of light—directly on the photographic film. This method has the great advantage that no special arrangements are necessary, as e.g. with the Kerr cell or the Wilson chamber. The sources of error are thus reduced to a minimum and the discharge can take place perfectly undisturbed in its natural environment. It may be assumed that the pre-processes of the discharge, in which the excited states and ionization by collision begin to make themselves felt, are accompanied by emission of light. The main difficulty is constituted by the extremely weak emission of light and its short duration. A dark-adapted eye may perceive the light phenomenon in a dark room, but the intensity of light is scarcely sufficient for the photographic film. The wave-length of the light is probably unfavourable to the film as well. It is true that many pictures of corona are reproduced in the literature, but they give no representations of the single streamers, only superimposed photographs of several consecutive impulses.

The photographs presented here, which were taken with a quartz rocksalt lens system carefully adjusted, brought new results with reference to the mechanism of spark discharge. We succeeded in recording on the film single streamers and the phases of the discharge process. The discharge is constituted by 3 successive phases, viz. two prephases and the main stroke. As it is not yet clear to what extent the two first phases are identical with the usual preprocesses (electron avalanche-streamers), we will designate them for the present as the first and the second phase of spark discharge.

b. First phase of spark discharge.

If a gap, longer than δ_0 (Fig. 2), is exposed to a positive impulse of variable voltage value, it remains dark at a low voltage, without any light phenomenon whatever at the electrode. With gradually increasing crest value of the voltage, visible blue processes appear at the electrode. This phenomenon does not appear gradually as the voltage increases—no prephenomena are seen at the previous low voltage values—but takes place suddenly with fully developed structure at the corona voltage. This phenomenon constitutes the first phase of the spark discharge, preceding all predischarges. In our experiments, the discharge always begins with this first phase. This fact has been clearly established for spheres of 1.44, 3.2, 6.2, 15, 25 and 50 cm diameter. Because of uncontrollable distribution of field, our tests have not been extended to point electrodes.

The first phase consists of one or several simultaneous elements. The element has an arborescent structure: the crown, consisting of long, faintly luminous filaments, is situated on a short, strongly luminous stem. Both these parts are invariably present, and both of them are probably indispensable to the formation of the first phase. We have not been able to photograph elements consisting of one part only. Fig. 3 gives four records of the first phase, taken from a great number of photograph series, with four different diameters of sphere (6.2–15–25–50 cm). They show that the structure remains unchanged, although the dimensions of the first phase increase with the diameter of the sphere. A further difference is that the larger sphere has a brighter first phase and consequently is easier to record on the film. The smallest sphere used in the experiments (diameter 1.44 cm) displayed so small an intensity of light that the phenomenon was fully visible only on the negative and could not be further reproduced. If only one element is present, the stem is mostly rectilinear. If the first phase consists of two or more elements, the stem may also be slightly curved. On the surface of the sphere the stems are always perpendicular. In the case of one element, their base is mostly at or near the lowest point of the sphere, where the field of the surface is strongest. This is not, however, invariably the case: sometimes the stem may be found in other parts of the lower hemisphere, the position of the base changing from one impulse to another. The base is rarely situated on or near the meridian; the points are generally grouped together in the lowest part of the sphere. Delayed elements, the stems of which are not situated on the surface of the sphere but branching off from the stem of the actual element, are rarely to be seen (Fig. 3 b). The base may frequently be observed to keep attached to one point of the electrode during a number of consecutive impulses. This point follows a turning of the electrode, which is to be explained in each case by the properties of that part of the surface of the sphere.

On a highly diminished photograph the stem generally seems cylindrical and

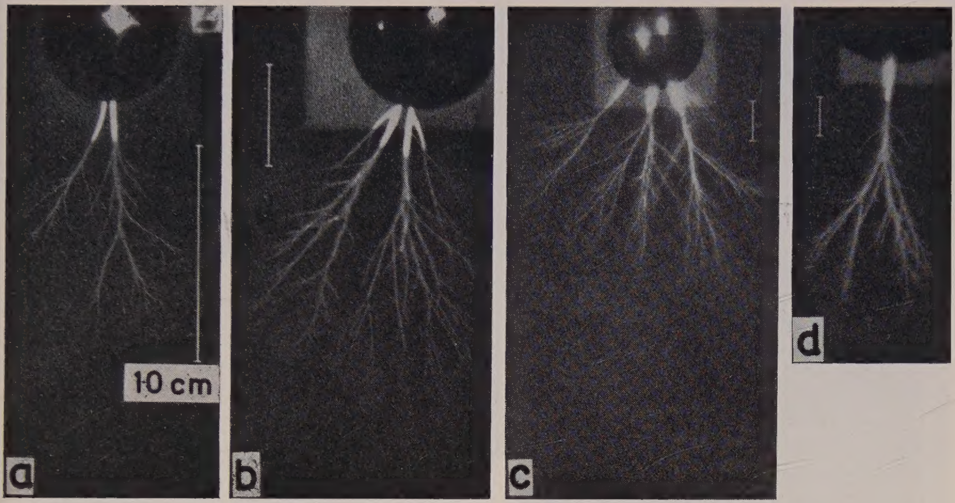

Fig. 3. The first phase of spark discharge for various diameters of sphere: a–6.2 cm, b–15 cm, c–25 cm, d–50 cm diameter. The first phase consists of: 1 element in d, 2 elements in a, b, and 3 elements in c. Each element consists of stem and crown.

its brightness to be distributed uniformly over the whole length of the stem. On photographs taken at close range (Fig. 4), however, the stem has another aspect: it is seen to have a cone-shaped core, standing with its tip on the surface of the electrode. On the photographs this place is often marked by a small dot, probably caused by reflection on the surface of the sphere. The brightness of the tip half of the core is greater than that of the base part, where the brightness decreases gradually. The core is surrounded by a more faintly luminous tube, which, strangely enough, does not extend to the surface of the sphere, but is absent or very faintly visible over a distance of 1.5 mm. The following approximate measures of the various parts of the stem were obtained from a photograph of 1/3 of the natural size, the diameter of the sphere being 6.2 mm:

Diameter of luminous points on the surface of the sphere	0.3 mm
Diameter of core at the tip	0.2 mm
Diameter of luminous tube or of core at the base	2–3 mm

The luminous filaments forming the second part (the crown) of an element in the first phase may be connected with the stem in various ways. One of the filaments is apparently an extension of the stem. In its further course it splits into smaller and ever finer single filaments. Some of the filaments are frequently situated directly on the stem. The filaments grow ever finer towards the ends, and their brightness decreases gradually, till finally they are invisible on the film. It is consequently impossible to establish sharp limits of the filaments or to measure the length of the filaments exactly.

All filaments together form the crown of an element in the first phase and occupy a certain part of the space in front of the electrode. An important fact should be mentioned in connection with the space of the crown. If the first phase consists

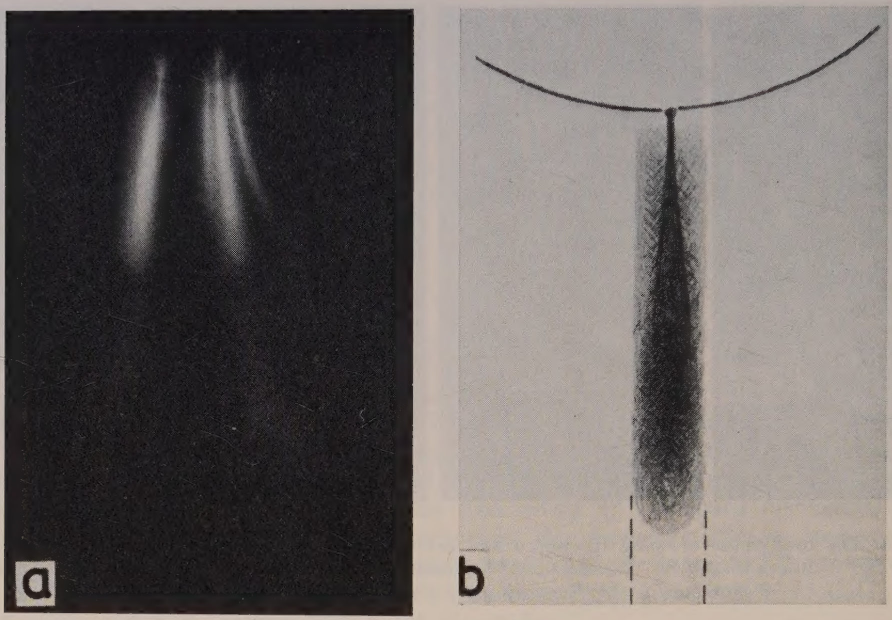

Fig. 4. Photograph at close range of the stem. Diameter of sphere = 6.2 cm, gap length = 30 cm, corona voltage = 140 kV. a—photograph in 1.43 natural size; b—schematized picture.

of several elements, the various spaces adhere closely to each other, but in no case were the spaces of the single elements found to be entwined or the filaments to cross each other. This explains the presence of curved stems: one element adheres to the adjacent one, the boundary of which is not rectilinear, but curved, and the stem and the crown adjust themselves to this boundary (Fig. 3 a and 6).

With the chopping method we could record not only the division of the discharge into single phases, but also the originating process of the first phase. It is also possible to determine the duration of the development. The chopping sphere-gap of 150 cm diameter operated with gap lengths below 20 cm. The field in the spark gap may be regarded as approximately uniform. The time lag is very small in such fields, for higher impulse ratios up to about $2 \cdot 10^{-8}$ sec. (13). Fig. 5 gives some photographs of the development of the first phase, taken with the method mentioned. On the threshold of visibility, i.e. at the shortest chopping time, a faintly luminous, short and comparatively thick streak of indistinct limits becomes first visible, with no or very little branching at the end and running perpendicularly to the surface of the electrode. The upper end of the filament, which adheres to the electrode, is much brighter than the filament itself and is to be regarded as the beginning of the stem. Already in its first visible stage the first phase thus possesses both parts: stem and filament. The photographs show that the stem starts as a luminous base of the short filament and develops further in the channel of the filament, as the filament grows. It is seen that in the fully developed first phase the stem may be defined as a strongly luminous upper part of the main filament. A remarkable conclusion may be drawn from the above: the two parts are inseparable during the growth of the first phase, the development of both taking place gradually.

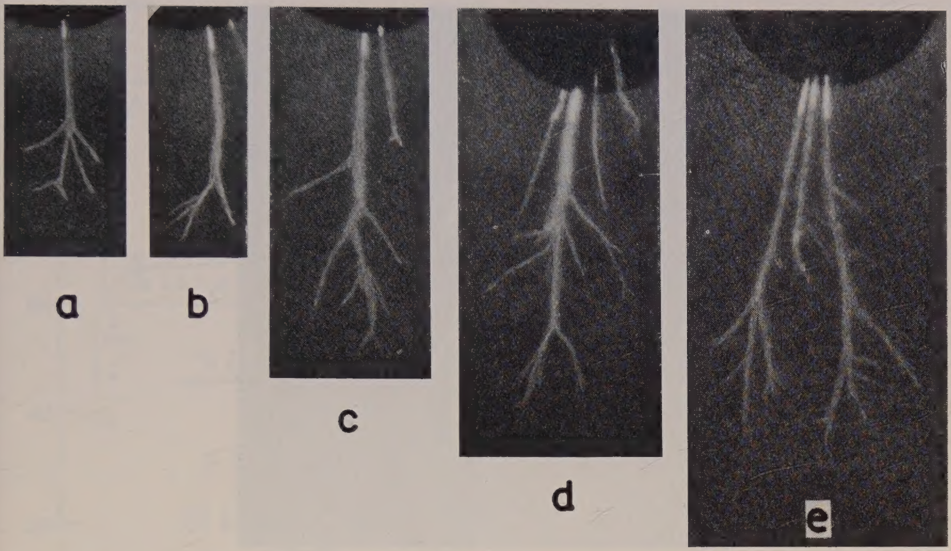

Fig. 5. The origin of the first phase. An element has a strongly luminous upper part (stem) already at the onset stage.

As to the time of development of the first phase, it was found that a noticeable shortening of the first phase could be brought about only if the impulse ratio of the chopping sphere-gap was 1.4. At the value 2 the development of the first phase was completely suppressed. It may thus be established preliminarily that the time of development of the first phase is of the order of 10^{-8} seconds. A more exact determination of this value will be made in the course of future investigations.

The state of the ionization in the space around the electrode is probably not uniform, but varying with the time and place. The movement of the electrons caused by the influence of the electric field of short duration traces various figures in the space. The luminous tracks running in the direction of the electrode resemble each other but are by no means exactly alike—the development process of the first phase is highly irregular as to its time and place and influenced by accidental circumstances. This explains why the dimensions of the single elements in a series of impulses are not alike. Even the various elements of one impulse are of different size and do not appear simultaneously: in the picture one may observe not only fully developed elements but also beginning, short and incompletely developed elements (Fig. 6).

The above-mentioned facts should be kept in mind in connection with the determination of the dimensions of the first phase. In the following, the measuring of the filament and stem lengths with a sphere of 6.2 cm diameter will be described as an instance. The lengths were measured from photographs, only the fully developed elements being taken into consideration. The first series of photographs were taken along the corona voltage (a–b) with varying gap length (Fig. 7). This series contains 10 photographs from No. 220 to 178. The second and third series were taken along two invariable gap lengths of 71 and 150 cm respectively (d–e and b–c): 6 photographs from No. 263 to No. 235, and 10 photographs from No. 178 to No. 300. The filament and stem lengths thus obtained are recorded in Fig. 7

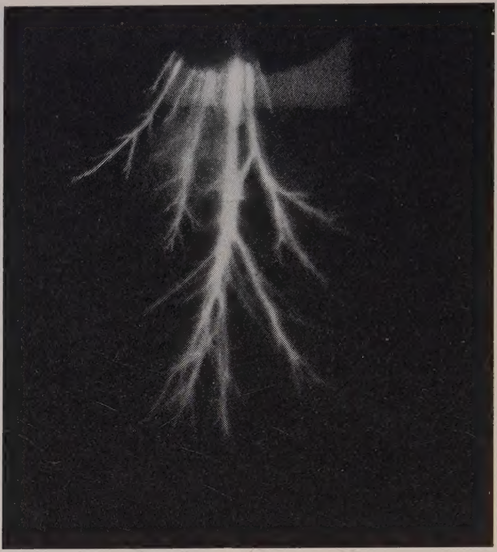

Fig. 6. The single elements of the first phase do not develop simultaneously.

as a function of the voltage. The numbers of the photographs given at each point of measurement apply to both curves (stem and filament length). When regarding the curve of stem length, the irregular points of measurement, spread around a middle value, are conspicuous. The curve is best represented by a horizontal straight line, i.e. the stem length is independent of the voltage and consequently also of the gap length down to the critical gap length (point a). In the present case (sphere of 6.2 cm diameter), each point of the triangle abc has a stem length of 1.8 cm.

It was not the object of the present investigation to determine the stem length at gap lengths below the critical length. Preliminary measurements with a sphere diameter of 25 cm showed that with short gaps (about 3 times the constant stem length) the stem length increases up to about 1.5 of the critical value. If the gap length reaches this value, the stem covers the whole gap, and no filaments are formed.

So far the stem. We now return to Fig. 7 in order to point out some properties of the other curve (filament length). Here the voltage is the main factor determining the length of the filaments. The influence is very marked at high voltages, and weaker at low voltages. Near the critical gap length (point a), the filament length approximates to a constant value l_0. The gap length has no direct influence on the filament length, as is seen from the following examples: the photographs No. 175 and 301 (Fig. 7), which were taken at the same voltage (384 kV) but with different gap lengths (124 and 150 cm respectively), have approximately the same filament length—26 and 25.6 cm respectively. The photographs No. 288 and 300, on the other hand, were taken with the same gap length (150 cm) but at highly different voltages (275 and 726 kV respectively); the filament lengths differ greatly —19 and 102 cm respectively.

The behaviour of the stems and filaments is about the same from 1.44 up to 25 cm diameter of the sphere. At a diameter of 50 cm it was impossible to reach the

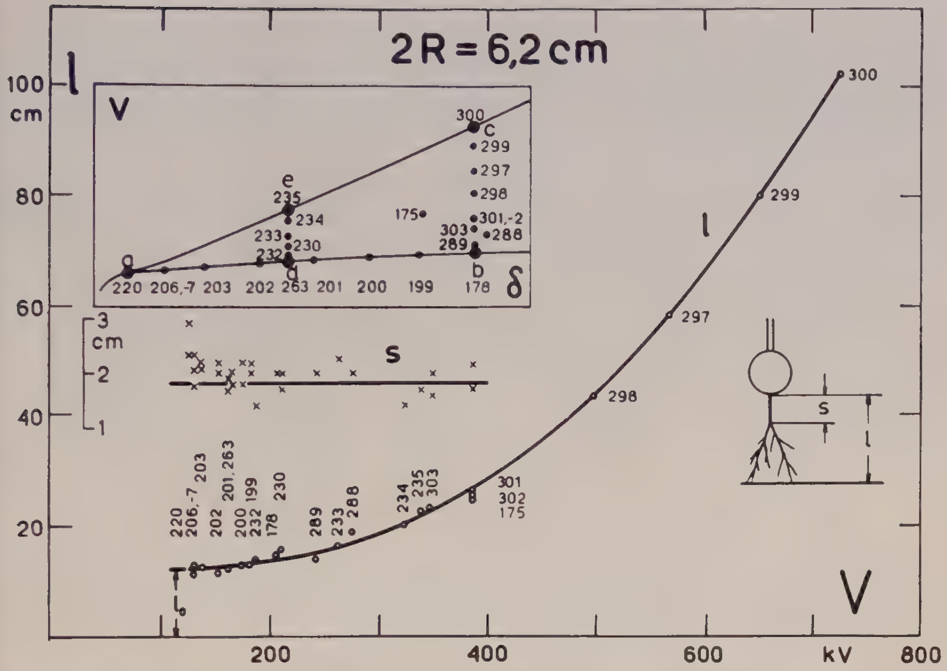

Fig. 7. Dimensions of the first phase for 6.2 cm diameter of sphere: stem length (s) and filament length (l) plotted against the voltage (V). The numbers at the measuring points indicate the numbers of the photographs and refer to both curves (s and l). For orientation as to the position of the measuring point in the voltage characteristics, a schematized V–δ curve is given.

critical gap length (point a) with the given voltage. Hence only the stem length, but not the filament length, was measured for this electrode. The measured values will be arranged according to two points of view.

Firstly, then, it is interesting to establish the dependence of the length of the stems and filaments on the diameter of the sphere. Table 3 gives the stem and filament lengths obtained with spheres of varying size, the filament lengths recorded being the constant values at the critical gap length (l_0 in Fig. 7).

Table 3.

Stem and filament length at the critical gap length.

Diameter of sphere $2R$ cm	Stem length s cm	Filament length l_0 cm
1.44	0.55	2.6
3.2	0.9	6.5
6.2	1.8	12.2
15	4.3	26
25	7.2	48
50	14.4	—

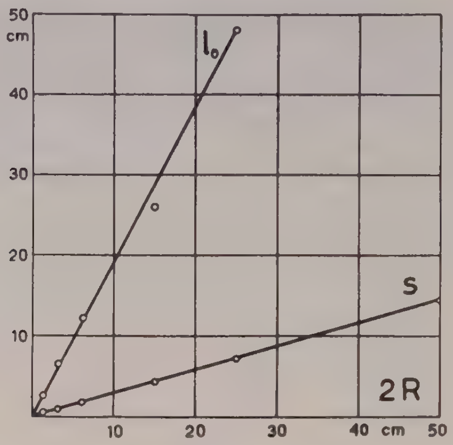

Fig. 8. Dimensions of the first phase: stem length (s) and filament length (l_0) at corona voltage as a function of the diameter of the sphere.

The curves in Fig. 8 demonstrate the dependence of the length on the diameter of the electrode. Both functions are rectilinear and may be represented by the following experimental equations:

$$l_0 = 3.84 \text{ R} \qquad\qquad s = 0.58 \text{ R}.$$

From this follows:

$$\frac{s}{l_0} = 0.15$$

i.e. at the critical gap length the stem measures 15 % of the filament length for all electrodes.

The relations are quite different in the case of the filament lengths, if they are regarded as a function of the gap length along the corona voltage (a–b, Fig. 7) or along the breakdown voltage (a–c). The curves for filament length are given in Fig. 9; the straight line with the angle of 45° represents the gap length.

The filament length along the corona voltage changes very little (three a–b curves), because the voltage does not increase much with the gap length. The filament length may be considered constant here without much error. In the points a_1–a_2–a_3 the length of the filaments is the same as the gap length. From this point on, the first phase can traverse the whole gap with its filaments; the curve for filament length changes into the δ-line. The first phase cannot develop fully in this region, the crown has to adapt itself to the gap length. It seems likely that the points a_1–a_2–a_3 in Fig. 9 are identical with the critical point a of the voltage curve in Fig. 7 or the point b in Fig. 2. This important surmise is corroborated by the data in Table 4. The accordance between the numbers is satisfactory.

Another property is apparent from the crown curve at the breakdown voltage (three a–c curves in Fig. 9). At the breakdown voltage above the critical gap length, the filament length is lower than the gap length. Although the filament grows with the voltage, it cannot cover the gap completely. The difference for the various

Table 4.

The critical gap length δ_0 compared with the filament length l_0.

Diameter of electrode cm	6.2	15	25
From voltage curve (Fig. 1) δ_0 cm	12	25	50
From crown curve (Fig. 8 and Table 3) l_0 cm..	12.2	26	48

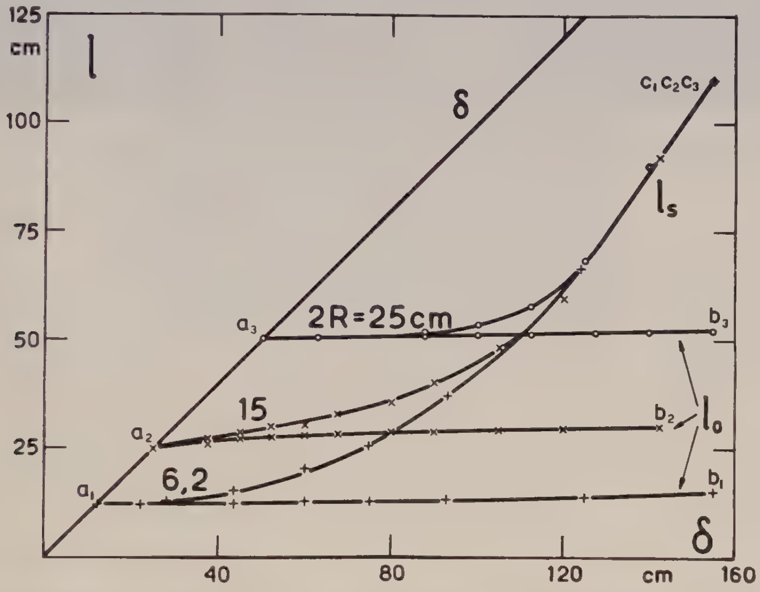

Fig. 9. Dimensions of the first phase: filament length at corona voltage (l_0) and at sparking voltage (l_s) as a function of the gap length and the diameter of the sphere (parameter). The straight line (δ) represents the gap length.

spheres increases with the gap length. If different spheres are compared with each other, the differences are greater for large electrodes than for small ones. The curves for different spheres merge into a common curve at a certain gap length: for the diameters 6.2 and 15 cm at a gap length of 110 cm, and for all three diameters at a gap length of 125 cm. Above the gap length 125 cm, all three curves form a common curve. This fact is to be connected with the common voltage curve (Fig. 1 and 2) above the gap length 100–110 cm. The common part of the crown curves a–c (Fig. 9) seems to display a *constant difference* from the gap length. This difference, however, is not influenced by the size of the sphere (6.2–25 cm). This observation will have to be carefully controlled, as it is possible that the first phase is so unstable shortly before the sparking state, that our chopping method is too slow to be able to measure the true filament length. This ought to be investigated more closely in the future, possibly with other chopping methods.

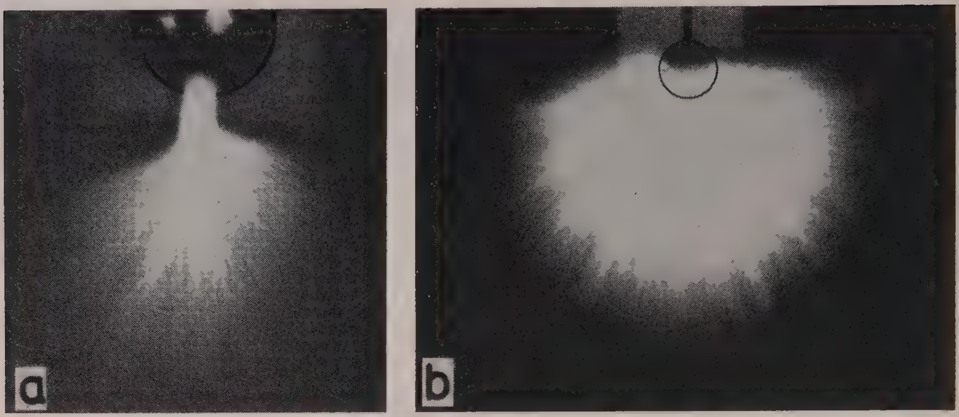

Fig. 10. Superposed photographs of the first phase. a—30 impulses with 6.2 cm sphere at stable base of stem b—10 impulses with 15 cm sphere at mobile base of stem.

If the first phase of several consecutive impulses are recorded on the same photograph-plate, the well-known picture of the positive corona is had (8, 14, 5, 15, 16, 17). If the base of the stem remains somewhat stable on the surface of the sphere during the photographing, the picture presents a thick stem extending from the sphere with a broad luminous brush at the end (Fig. 10 a). If, on the other hand, the base moves over the surface of the electrode in the course of the superposed photographs, the various single pictures surround the lower hemisphere of the electrode, which seems completely covered by a bright glow (Fig. 10 b).

Yet two points will have to be considered in this survey: the influence of overvoltage and of the material of the anode on the first phase. The influence of overvoltage is constituted by the increased number of elements: the more overvoltage, the more elements. Regardless of this, however, the single elements keep their structure and appearance (Fig. 11). The question of the influence of the material has been decided by additional experiments. The first phase with a sphere of 3.2 cm diameter and various kinds of material (copper, brass, aluminium and carbon) was photographed. The pictures present no difference between the materials mentioned, the first phase remains unmodified as to its appearance, structure and dimensions. The well-known fact that the corona is not influenced by the material of the electrodes in air at atmospheric pressure (8) is thus corroborated for the material of the anode in the case of positive impulse discharge.

c. *Second phase of spark discharge.*

The first phase is followed immediately by the second phase of spark discharge —in the following called simply the *second phase*. It should be mentioned in advance that it is identical with a positive streamer and develops from the anode in the direction of the cathode. Its luminosity is considerably greater than that of the first phase. The comparison will be elaborated in detail later on.

The second phase starts on the surface of the anode. The starting-point is the base of the first phase on the surface of the anode sphere, from which a strongly luminous channel of about 0.2 mm breadth grows forth. In its origin it uses the

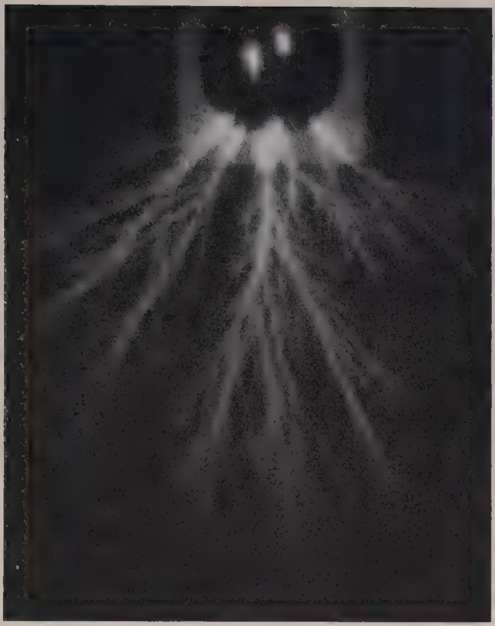

Fig. 11. The influence of overvoltage on the first phase is constituted by increase of the number of elements.

ionized path of the first phase, i.e. it runs along the centre of the stem. It does not utilize the stem fully in its further course: at a certain distance the channel leaves the stem and changes into one or several curved filaments. It leaves the stem at an angle of up to 90°. This process may take place in various ways: the channel may be converted at once into one or several curved filaments, or the branching may take place successively in various places (Fig. 12). The most important feature of this process, as observed from the photographs, is the fact that the last point of branching never coincides with the end of the stem. The end of the stem does not seem to be of particular importance; at any rate the filaments of the second phase never originate from it, the point of branching invariably being nearer the electrode than the end of the stem. The state of ionization is probably not uniform in the stem during its development; it is strongest in the core (cf. Fig. 4). The end of the stem, where the core gradually looses its luminosity, is no longer sufficiently ionized to serve as a path for the filament of the second phase.

When the filaments of the second phase have left the stem, they spread arborescently in the space in the direction of the lower plane electrode. This process takes place with the help of very fine faint filaments, which are visible at the ends in the shape of short tufts. The tufts are crossed by a spark in one or several places, and thus several branches may appear simultaneously. This gives the second phase its arborescent form (Fig. 13).

The branches are to be conceived as quasi-metallic plasma channels. They collect the electrons from the space by the tufts at their ends. The electrons are conducted to the anode through the branches. As the current increases continuously

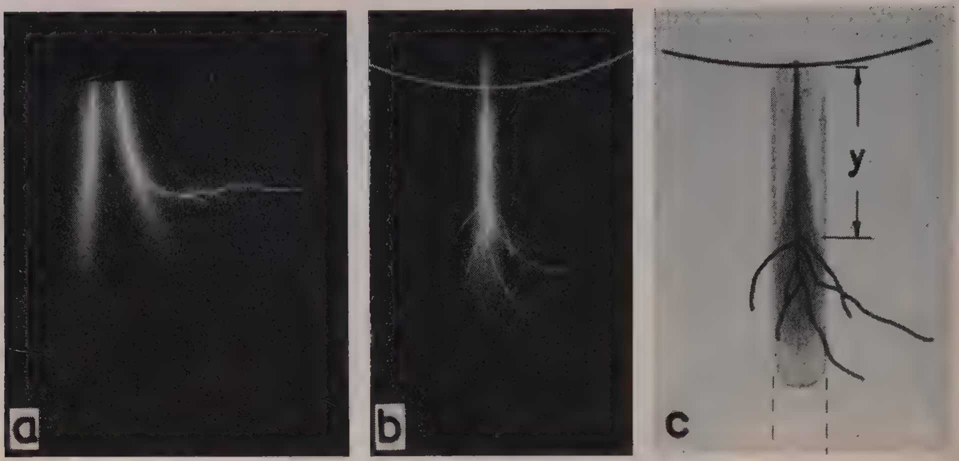

Fig. 12. The origin of the second phase. a—with one initial path, b—with several initial paths, c—schematized picture.

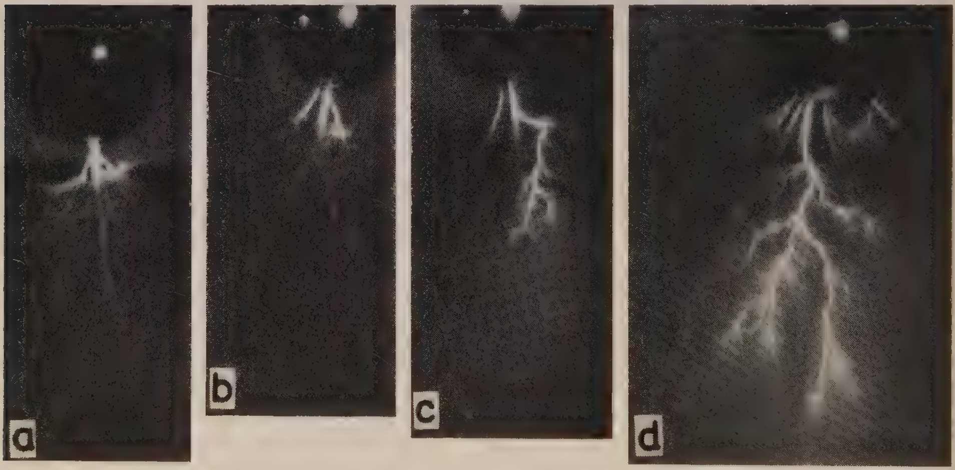

Fig. 13. The stages of the development of the second phase.

in the branches, the diameter of the latter grows gradually, the thermoionization effecting the further decrease of the resistance in the branches.

It was further established as a result of the experiments that the second phase after leaving the stem does not utilize any of the filaments of the first phase for its development. Their ionization is either extinct already, or the filaments offer no preference to the development of the branches of the second phase, which follows its own laws. The photographs show that the crown of the first phase and the branches of the second phase differ considerably as to their structure and appearance (Fig. 14).

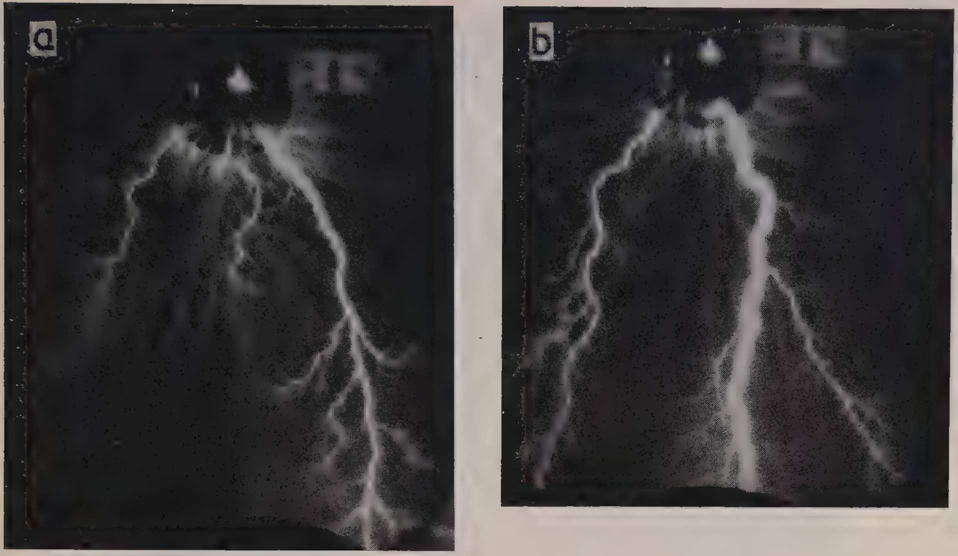

Fig. 14. The form of the faintly luminous filaments of the first phase differs greatly from that of the strongly luminous branches of the second phase. The picture gives only the upper part of the discharge. The round black outline seen below is not an electrode, but the edge of the film.

A further new process is observed during the early part of the second phase: a luminous bundle of rays comes forth from the ends of the branches, running in the direction of the plane electrode. The bundle first consists of a few faint rays, which do not penetrate far into the space. At a later stage the bundle grows brighter and broader and covers the whole distance down to the lower plane electrode. The rays run so closely together that the single rays cannot be distinguished: the bundle assumes the shape of a widely spaced glow. The path of the rays seems to adjust itself to the field lines of the gap. The further development of the branches of the second phase takes place in this widely spread bundle (Fig. 15). It appears from Fig. 15 b that only the ends of the branches are to be conceived as the source of the rays: no luminosity is to be seen in the space between fully developed branches. An enlarged photograph proves the bundle to consist of luminous paths, which do not run rectilinearly and do not resemble the filaments of the first phase and the branches of the second phase (Fig. 16). If the structure of the bundles is photographed under the same conditions during several successive impulses, the pictures present varying luminosity of the rays. This is explained by the varying length of the developed branches and bundles: shorter bundles have brighter rays.

The branches which have developed earlier increase in thickness during the continuous progress—on the photograph they are seen as the thicker ones (Fig. 14). One of them (if several are at hand simultaneously) will serve as channel for the main stroke later on in the third phase. The thickness of the branches is not uniform, the branches at the electrode being thickest. In the direction of the plane electrode they grow thinner by degrees. The thickening of the branches, observed optically on the photograph, may have two causes: it is either caused by a real increase of

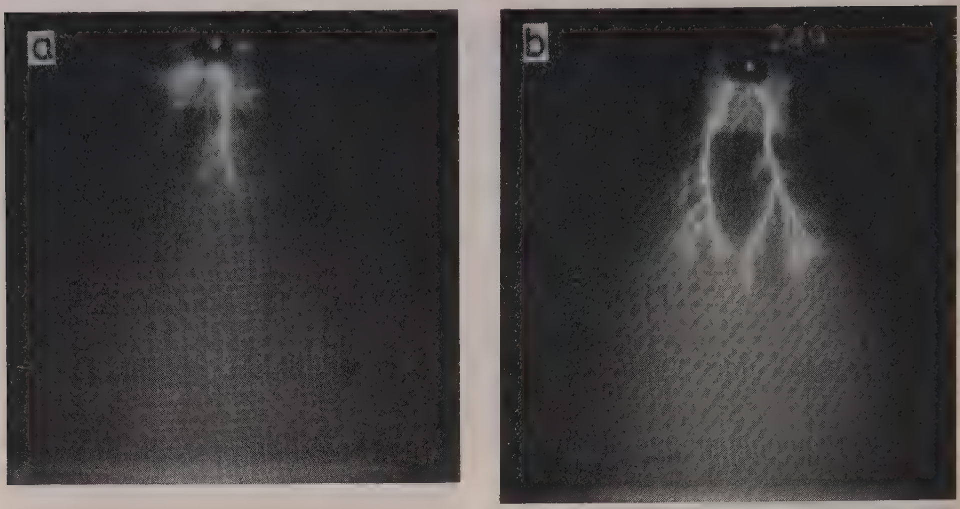

Fig. 15. The bundle of rays of the second phase. a—weakly developed, b—more developed. The plane electrode is visible in the lower part of the picture.

Fig. 16. Enlarged picture of the structure of the bundle.

the diameter of the branches, or it is a dazzle-effect of the increasing luminosity. Later, in the third phase, it will be shown that the latter supposition corresponds better to the actual facts than the former one.

It will further have to be investigated, whether a negative streamer does not grow forth from the lower plane electrode (the cathode) towards the branches of the

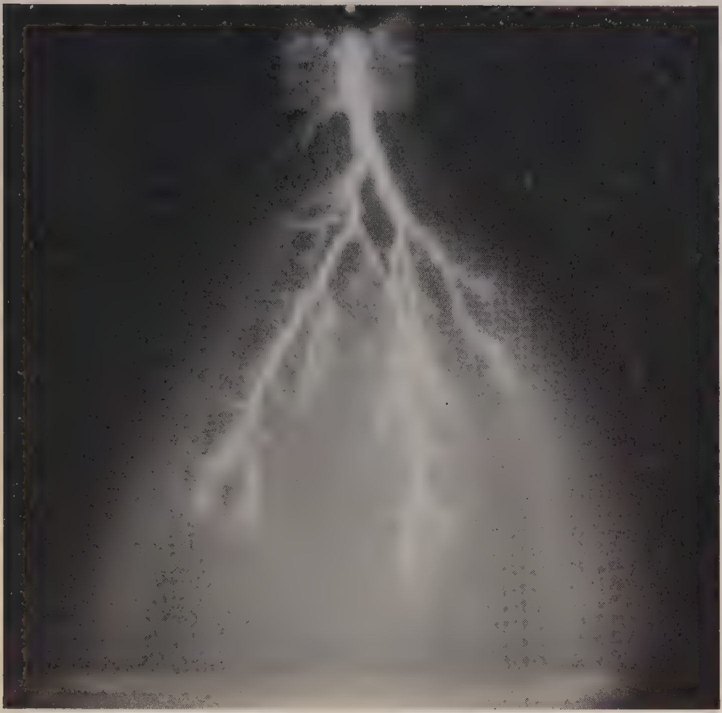

Fig. 17. The bundle is uniform also in the latest stages of the development of the second phase. No influence of the lower plate is visible.

second phase. The results of such an investigation would be of great theoretical interest, as they will establish whether the process of discharge plane-to-sphere is influenced also by the space of the plane and to what extent the cathode plate contributes to the mechanism of the discharge. A thorough examination of numerous photographic records leads to the conclusion that no streamers or other light phenomena (glow etc.) are developed at the cathode plate. This applies also to the latest stage of the second phase, when the ends of the branches have already approached rather near the plane. The rays of the luminous conelike bundle display no additional luminosity near the plane of the cathode, but are altogether continual all the way down to the surface of the plane (Fig. 17). On Fig. 18 the branches are photographed at a distance of only 10 cm from the cathode plate. No negative streamer growing in the opposite direction is visible, and the luminous tufts at the ends of the branches have their usual appearance. This proves that the process of the development of the branches remains unmodified all the way down to the lower electrode. We would not, however, regard the above-mentioned conclusion as final, as it is based on a few hundred photographs and only about 10 % overvoltage was used.

The formative time of the second phase should also be mentioned. This question (velocity and influence factors) will be treated more fully in a future work. In the present experiment it was only established preliminarily for a sphere of 6.2 cm dia-

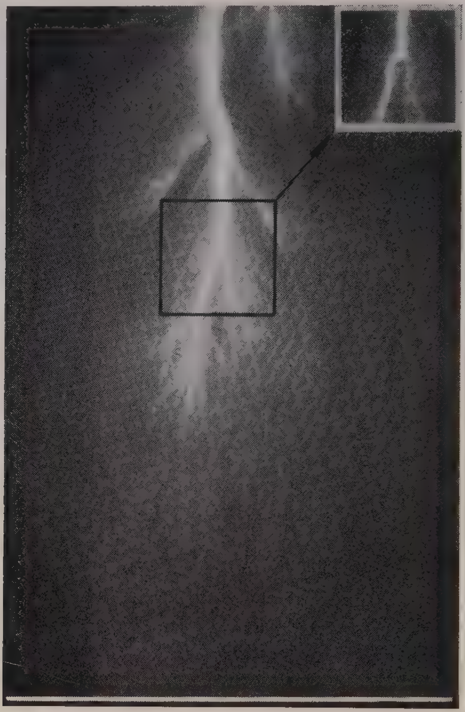

Fig. 18. The end of the conductive branch of the second phase is at a distance of only 10 cm from the plate (indicated as a white streak in the lower part of the picture). No channels growing from the plate towards the branch are visible.

meter at a gap length of 71 cm and 10 % overvoltage, that the formative time of the second phase amounts to about 20 μs at complete breakdown, i.e. considerably more than the formative time of the first phase. If the gap is exposed to an impulse wave of invariable crest value and a tail shorter than the formative time required for the second phase, the discharge cannot develop into a breakdown. The shorter the tail is, the earlier the development of the second phase is interrupted. This circumstance is utilized in photographing the various stages of development of the second phase: the parallel-coupled chopping gap was chosen and adjusted so as to ensure the desired correct tail time of the impulse wave. This explains also the fact, long well-known in high voltage engineering, that the voltage necessary to the breakdown in a gap depends on the time of the influence. The shorter the tail is, the greater must its height be in order to effect the breakdown in one and the same gap. This means that the crest value determines the formative time of the second phase. Naturally the influence of the impulse duration makes itself felt only if it is shorter than the formative time of the complete second phase.

The moment of the starting of the second phase remains to be determined. The photographs taken at corona voltage prove that the presence of the first phase only cannot be established with certainty for all impulses, but only for some of them. The corona voltage probably suffices also for the start of the second phase. An undisturbed picture of the first phase can generally be obtained only by chopping off shortly before the crest value of the voltage. It may be concluded from this that the second phase follows immediately after the first phase. The further progress of the second phase is determined by the voltage and the gap length. The branches cannot develop at corona voltage (point b in Fig. 7), but are restricted to the space in the immediate neighbourhood of the electrode (Fig. 13 a, b). It is true that the branches grow longer with increasing voltage (b–c in Fig. 7), but the increase is small. The conditions necessary to the development of the branches are at hand only at the sparking voltage (point c in Fig. 7), the second phase being able to grow undisturbed down to the cathode plate. The second phase thus appears immediately after the first phase, but is able to develop only at the sparking voltage.

d. Third phase of spark discharge.

The branches of the second phase are plasma channels of a falling character. When a branch reaches the cathode plate, it forms a quasi-metallic connection between the two electrodes with a channel of good conductivity, through which the impulse generator discharges. This process—the main stroke—will be called the third phase.

The main stroke does not form its own path, but utilizes the channels formed by the second phase. Frequently two or even more channels reach the plane electrode at the same time. In such a case the third phase has several channels at its disposal, and the main stroke splits into several sparks. The branches that develop later or run more slowly and therefore cannot reach the cathode are seen half-developed on the photograph. The current depends to a great extent on the electrical properties of the circuit, and the third phase itself only contributes its resistance of spark. The thickness of spark obtained on the photograph varies according to the photographic material, the conditions of exposure and the printing procedure. The measurement of the dimensions must be carried out with the greatest care. That the visible thickness of the spark on the picture does not correspond to the real thickness is evident on Fig. 19, where three separate sparks are represented. The real thickness, i.e. the thickness of the channel in which the current flows, is to be had from the pictures to the right (Fig. 19 a, b). The photographic negative of Fig. 19 c was not suitable for determining the real thickness of the spark. At the crest value 2 000 A of the impulse current, the order of the diameter of the channel is 1–3 mm (Fig. 19 b). The diameter of the accompanying voluminous glow may vary on the picture, according to the photographic procedure. The glow is only the result of the dazzle-effect. If the aperture is large, the glow may fog almost the entire picture, and the dimensions of the glow are hence of no importance to the treatment of the third phase. That only the channel and not the glow is conducting follows from the fact the small lateral branches issue into the channel and not into the glow.

No further gradation of the light within the channel could be observed photographically.

In the earlier stage, the branches of the second phase had a diameter of 0.2 mm, but at the main stroke, with a current strength of 2 000 A the diameter had increased to a value of 1–3 mm: the influence of the current strength on the diameter is evident. We now return to Fig. 14, 15, 17. As was shown above, the diameter of the growing branches increases with the length: the nearer the upper electrode the section is situated, the larger its diameter seems to be. This optical increase is mainly due

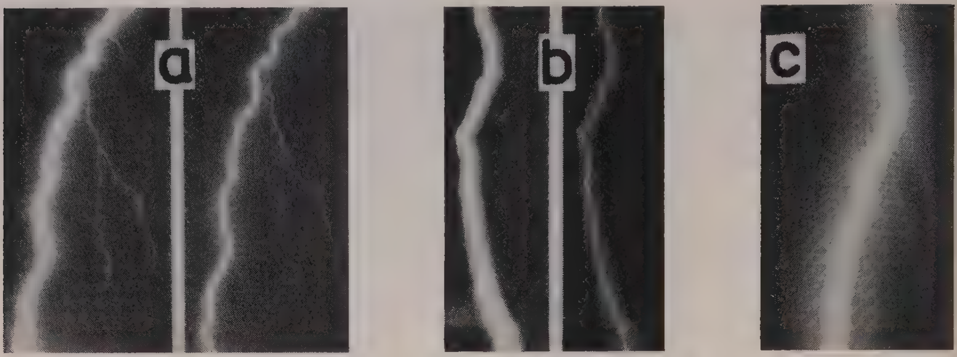

Fig. 19. The measurement of the thickness of the channel of the third phase (the main stroke) is possible only from suitable negatives (a, b). c—unsuitable negative.

to the dazzle; the small increase of the channel diameter itself is hardly visible on the picture.

The causes of the increase of the light intensity are easily inferred from the above. The current strength has increased in the branches, but the distribution is not uniform—the sections situated nearer the anode sphere conduct more currents than the lower, starting, parts of the branches. In the outer circuit the current increases with the length of the branches. This is caused by two circumstances: firstly the gap is bridged over to an ever increasing extent by quasi-metallic filaments, and secondly the bundle of rays appearing in the rest of the gap grows ever brighter. The formation of ions in the bundle probably increases, and the resistance in this part of the gap is lowered accordingly. The current, which was insignificant in the beginning of the second phase, increases gradually during the development of the second phase, and in the third phase it reaches a final value determined by the circuit constants.

To summarize: The final current is obtained in the third phase and depends solely on the discharge circuit constants. The process of the current increase takes place during the development of the second phase and is regulated by the pattern of branches. This conclusion is corroborated by an oscillogram obtained in earlier experiments (point-to-plane, $\delta = 177$ cm, 0.58 MΩ series resistance, Fig. 20). Similar oscillograms are given by Allibone and Meek (12, Fig. 5). In the present experiments, the question of the variation of the current was not investigated particularly.

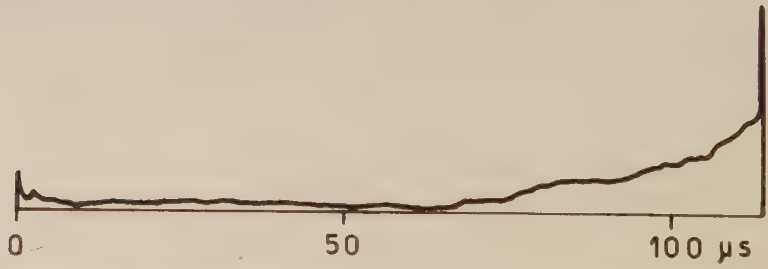

Fig. 20. Current oscillogram of a positive impulse with a series resistance of 0.58 MΩ. Diameter of sphere = 25 cm, gap length = 177 cm. Note the considerable current before the main stroke.

5. Discussion

a. Calculation of the field.

Of the many factors influencing spark development, the field strength should be the most important one, as new formation of charge carriers by ionization by collision cannot be imagined without sufficient field strength. In a point situated on the normal from the centre of the sphere to the plate at the distance y from the plate (8), the field strength is:

$$X_y = V \frac{2\delta[\delta^2(f+1)+y^2(f-1)]}{[\delta^2(f+1)-y^2(f-1)]^2}$$

X_y = field strength in the point, one coordinate being $= y$
δ = gap length
V = voltage.

In the case sphere-to-plane, the coefficient f is represented in the following way:

$$f = \tfrac{1}{4}[(2p-1)+\sqrt{(2p-1)^2+8}]$$

where $p = 1 + \frac{\delta}{R}$ (R = sphere radius).

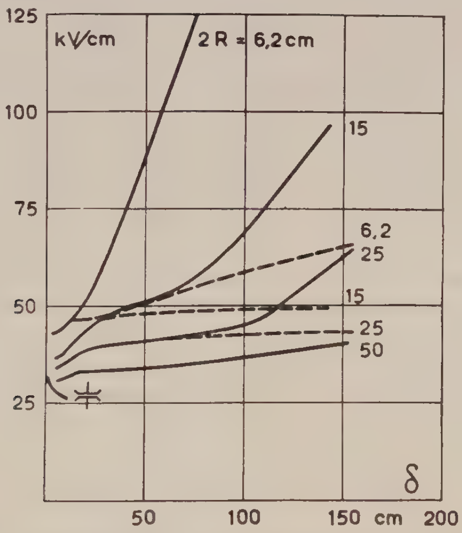

Fig. 21. Field strength on the surface of the spherical electrode (anode) at sparking voltage (full curves) and at corona voltage (dotted curves) plotted against the gap length and diameter of sphere (parameter). By way of comparison, the sparking field strength plane-to-plane has been inserted.

The calculated *field on the surface* of the sphere gives irregular curves (Fig. 21), similar to the well-known field values for a symmetric electrode arrangement (10). Neither the corona field nor the sparking field remains constant with the gap length. Nor are the fields for different diameters of sphere similar at one and the same gap length. Some characteristics of the curves will be pointed out: From a certain gap length on, the sparking field is proportional to the gap length for all sizes of sphere. The critical gap lengths—40, 105 and 112 for the diameters 6.2, 15 and 25 cm—are probably connected with those points of the voltage curve, where the latter changes into a straight line (Fig. 1 and Table 2). Further, both fields decrease with increasing diameter of the sphere. The longer gaps require a stronger field, all field strengths (even at small gap lengths) being higher than for the arrangement plane-to-plane.

The field at the end of the stem at corona voltage varies much less, as is seen from Table 5.

Table 5.

Limits of the field strength at the stem and filament ends at corona voltage.

Diameter of sphere cm	At the stem end		At the filament end	
	Gap length cm	Field strength kV/cm	Gap length cm	Field strength kV/cm
	1.8	24.2	12	3.84
6.2	4	18.3	80	2.26
	155	26.5	155	2.03
	4.3	21.2	25	4.64
15	10	17.2	80	2.16
	150	19.6	143	1.97
	7.0	20.3	50	3.16
25	30	16.6	100	1.86
	150	17.8	155	1.70
	20	16.6		
50	60	14.3	—	—
	145	15.8		

The values are influenced by the gap length and cover a range from 14.3 to 26.5 kV/cm. This result was hardly expected beforehand, as the field strength, to judge by the ionization by collision—which undoubtedly takes place in the stem—should not be below 23.4 kV/cm. The table, however, shows that the field strength, with the exception of the smallest sphere, is below this value, being smaller for the larger spheres. The space charge cannot be responsible for this, as the stem is the first phenomenon and the space charge does not appear until the first phase.

Still more difficult to understand is the field condition at corona voltage at the filament ends of the first phase. The values are between 1.7 and 4.6 kV/cm (Table 5), vary with the diameter of the sphere and the gap length, and are certainly too small to indicate ionization by collision in the filaments of the first phase. This is also evident from the photographs: the luminosity of the filaments is very weak and distributed rather uniformly over the whole length.

The curves for the *average gradient* between the spheres and plane, demonstrated in Fig. 22, finally show that the sparking field strength is about the same for different spheres at gap lengths below the critical gap length, or about 5 kV/cm (the exact values are: 4.86 kV/cm for 6.2 cm, 4.94 kV/cm for 15 cm and 4.99 for 25 cm diameter of sphere).

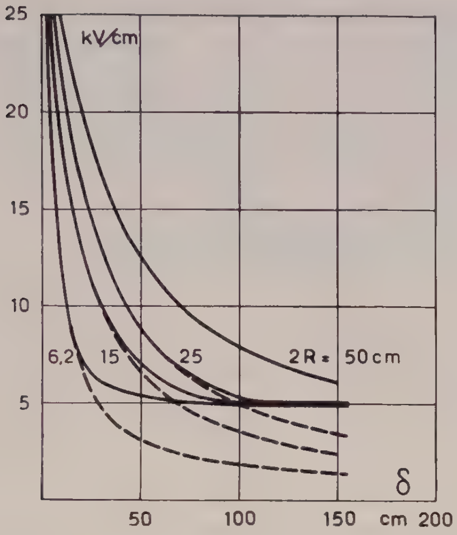

Fig. 22. Average field strength of the gap at sparking voltage (full curves) and at corona voltage (dotted curves) plotted against the gap length and diameter of the sphere (parameter). Note that the sparking field for gap lengths above $\delta \approx 100$ cm is about the same for different spheres (about 5 kV/cm).

b. The starting-point of ionization by collision in the space.

As is well known, ionization by collision first becomes appreciable when α reaches the value 1, which requires a field strength of 23.4 kV/cm in air at atmospheric pressure. It was interesting to study the movement in the space on the normal of the point ($\alpha = 1$) at corona and sparking voltage for various spheres and gap lengths. As is seen from Fig. 23, the distance (x) is influenced by the diameter of the sphere, the gap length and the character of the voltage (corona or sparking voltage). At short gaps the curves start at $\delta = x$, i.e. at the gap spacing values at which the field reaches the value 23.4 kV/cm on the surface of the plate. The distance decreases with increasing gap length, runs through a minimum, different for different spheres, and then increases again. At corona voltage the increase is so flat that the distance x may be regarded as constant for a certain sphere at a high δ value. At the sparking voltage, on the other hand, the increase is comparatively steep. A better survey is offered by the curves in Fig. 24, which give the distance x for various diameters of sphere. The variations of x influenced by the gap length is here established for each sphere by two limit values, between which the variable x values are situated. The inserted straight line, representing the stem length, shows that no ionization by collision can take place at the end of the stem if the diameter of the sphere exceeds 10 cm. This may be considered to be the cause of the observation mentioned above, viz. that the second phase never develops from the end, but from the middle of the stem. The distance between this point of branching and the surface of the sphere, measured on the photographs, has been inserted in Fig. 24 in the form of points, which accord well with the curve for ($\alpha = 1$). This means, however, that the second phase can use only the part of the stem where ionization by collision takes

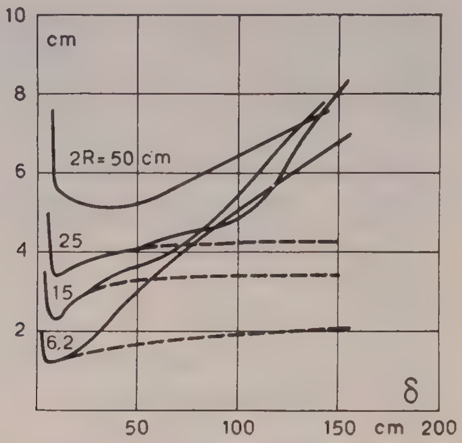

Fig. 23. The distance of the point ($\alpha = 1$) from the surface of the sphere at sparking voltage (full curves) and at corona voltage (dotted curves) as a function of the gap length and diameter of sphere (parameter).

place, and the farthest part of the stem can have no influence on the progress of the second phase.

c. *The mechanism of spark discharge sphere-to-plane with long gaps.*

The picture of the development of the *positive discharge* outlined here cannot be considered complete for the arrangement sphere-to-plane with long gaps, but is only an attempt at picturing a likely variant on the basis of the experience won. It is evident that further thorough investigation and experimental corroboration of various details is necessary in order to arrive at a fully satisfactory description of the development of the process of spark discharge. We hereby want to turn the discussion of this question in a new direction.

The *first phase of spark discharge*, which consists of a faint and uniformly luminous crown of filaments situated on a short and bright stem, appears fully developed in the space at a critical voltage = corona voltage. If the voltage is somewhat lower, the phenomenon is completely absent. Thus a certain voltage threshold has to be reached before it can appear. The distribution of the field in the space found at the start (Table 5 and Fig. 24) shows that ionization by collision can take place only in the upper part of the stem (a few cm from the surface). The field is not sufficient for ionization by collision in the farther part of the stem and in the filaments of the crown. The filaments should be regarded as non-conducting and consisting of excited molecules, and it should further be assumed that the electrons here move in the direction of the anode under the influence of the field. Motion of the ions should be regarded as unlikely because of the short duration. Otherwise expressed: the field "exhausts" the electrons from a certain sector of the space (the crown). The velocity of the electrons—provided that it is determined by the field alone—may amount to a few cm per microsecond (the field = a few kV/cm). As this weak field cannot dissociate the electrons from the ions and molecules, some other source of the electrons will have to be found. Production of electrons by the photoelectric effect is excluded under the prevailing conditions: 1) the ex-

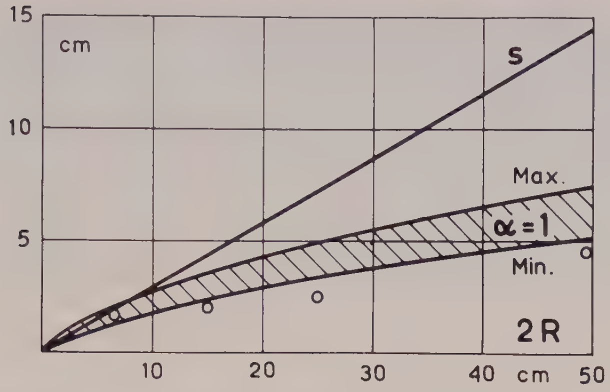

Fig. 24. Stem length (s) compared with the point (α = 1) in the space at corona voltage. The circular points represent the distance y (see Fig. 12).

periments were performed in a completely darkened room; 2) no light phenomenon is visible before the first phase; and 3) the stem and the crown appear simultaneously. As is well known, the air contains small amounts of radioactive substances. Let us assume that these substances constitute a source of electrons. Sufficient amounts of free electrons with short life are probably always present in the spark gap. A balanced state probably prevails in the process of formation and recombination of the ions in the air. The "exhaustion" of the electrons in the crown space produces a disturbance of the balanced state, and a positive space charge is formed there. The restoration of the initial condition in the space requires some time. The observation that a later element of the first phase at the same impulse, developed with short time lag, never penetrates into the crown space (space charge) of the earlier developed element, proves that this time is longer than some microseconds. Another observation was made at corona voltage and successive impulses: the adjusted voltage does not suffice for the formation of the first phase of each impulse, unless the time interval amounts to about 10 sec. If the time interval is only 2—5 sec, the first phase appears only in a few impulses in the beginning, whereas the following impulses cannot cause the first phase. Thus the upper limit of the time of restoration is presumed, in our case at a value of about 5 sec. This phenomenon seems to be explained by the lagged activity of the source of the ions, i.e. the radioactive substances. A field influence is excluded, as a sufficient field exists only for about 50 μs. After a certain space of time, the original state of the ions and electrons and the electrical properties of the space are restored.

The high-tension hall, in which the experiments were performed, has been found (18) to have higher ion-density than open air: 10 000 n^-/cm^3 and 11 700 n^+/cm^3, as compared with 900–3 500 n/cm^3 in open air. This is explained by the increased amount of radioactive substances in the air of the hall.

The lumination of the filaments of the crown proves that the velocity of the electrons is much greater here than that calculated from the field—a few cm/μs. It seems incredible that the electrons moving so slowly should be able to cause the excited states in the luminous filaments. It is more likely that the accelerated electrons—under the influence of the local fields—exert certain powers on the other electrons. Probably some kind of electronic chain is formed. The velocity of the electrons in this chain increases in the direction of the anode because of the growing strength of the field, the velocity being particularly great in the stem, where ionization by collision takes place. A kind of "exhaustion action" makes itself felt: the electrons that are nearer to the sphere, especially those in the stem, exert an accelerating influence on the neighbouring electrons farther away, and the velocity of the electrons in the entire chain, i.e. the filaments of the crown, is probably made more or less constant. A certain critical velocity has to be reached (as is done at corona voltage), before an element of the first phase can develop. With the help of this conception it is easy to understand the threshold of the voltage necessary to the sudden formation of the first phase, as well as the obligatory necessity of both parts (stem and crown) in an element of the first phase. The stem is the main source of supply for the necessary formation energy; a contribution to the balance of energy is probably given also by the single parts of the chain with their own electronic velocities produced by the field. This is corroborated by the observation that none of the calculated stem factors remains constant with increasing gap length—neither the field strength on the surface of the sphere nor that at the end of the stem; also $\int \alpha dx$ increases with the gap length.

The crown of an element of the first phase thus occupies a space that has a space charge. As no electrons are present in the crown space any more and could not be restored during the impulse time, the neighbouring elements developed with short time lag cannot develop any more in this space, which is free from electrons. They utilize the adjacent space sectors, which are still in their initial state. The elements develop close to each other, each having its own space sector. In the final stage of the first phase the spacing is consequently split into single sectors of space charge, i.e. non-uniform as to its electrical properties. The sectors adjoining the sphere (the stem) have marked ionization by collision and carry off large numbers of electrons through narrow channels. This is where the second phase starts, the thermoionization probably being a factor of predominant importance.

The starting-point of the *second phase of spark discharge* is the base of the stem on the surface of the sphere. From here a plasma channel of high conductivity is developed, utilizing the core of the stem in its initial stage, thus being rectilinear. Fig. 24 shows that the second phase utilizes the core of the stem only as far as the point ($\alpha = 1$). It may be inferred from this that the track in which ionization by collision takes place either offers favourable conditions for the development of the plasma channel or is a conducting plasma channel itself.

During the further process the stem has no longer any favourable influence on the development of the second phase, which leaves the stem at an angle of frequently up to 90° and proceeds in the space. The further process takes place on the surface of the crown, where the branches of the second phase are offered better conditions of development and constitute a kind of gliding spark. The bend at the transition of the channel from the stem to the surface of the crown is visible later on at the spark further on and constitutes a characteristic feature of the spark at long gaps (19). While the part of the channel running in the stem is rectilinear, the channels developing farther on the surface of the crown sector (in the following called branches) are of a typical arborescent form. The branches grow with the aid of fine luminous tufts developed at their ends. The length of the tufts is of the order of 5 mm and seems to be independent of the size of the anode sphere. The tufts consist of many very fine, approximately rectilinear channels. One or two of them (rarely more) take over the leading part in the growing of the branches, forming brighter tracks (a spark is probably formed in the tufts), at the ends of which new tufts grow forth. This successive formation is to be regarded as the cause of the zig-zag form and branching of the branches of the second phase. When a branch is to serve as the path for the subsequent main stroke, the form of the spark is thus already determined. Because of many successive spark jumpings in the tuft, the time of development of the second phase is comparatively long for long gaps, about 20 μs.

A bundle of rays (in the following simply called bundle) develops outside the tuft as well, at the ends of the branches. On the photographs taken at long range it is seen as a diffuse glow directed towards the plate. The place of origin of the bundle (the ends of the branches or of the tufts) could not be established on the basis of the photographs. The bundle may also possibly be a continuation of the tuft. The properties of these two kinds of formations are, however, different. The tufts are short and seemingly little or not at all influenced by the size of the sphere and the voltage. The range of the bundle, on the other hand, depends on the voltage, the gap length and the diameter of the sphere. The bundle covers the whole gap down to the lower plane electrode only at sparking voltage. A breakdown can take place only if the condition enabling the bundle to traverse the gap is at hand. It seems justified to derive both—the tuft and the bundle—from the photo-effect in the gas. The question whether the two forms could not be explained by different wavelength or range of the radiation emanating from the ends of the branches cannot be decided until more exhaustive investigations have been carried out.

The property of the branches first to spread on the surface of the zone of discontinuity, and the fact that the branches do not run in the tracks of the crown filaments, seem to indicate that the first and the second phase are determined by different development mechanisms. The bundle of the second phase enters the crown volume of the first phase in its later stage, covers the whole spacing and provides the electron production necessary to the development of the branches. In the bundle the branches develop further by the aid of the tufts, collect the electrons and lead them, like a metallic conductor, down to the anode. The more a branch develops, the more does it carry off the current—a sure condition for thermoionization and uninterrupted increase of the conductivity of the branches. The luminosity of the branches increases, and they seem thicker on the photographs, which is mainly due to the increased intensity of light. Also the bundle grows broader and brighter; its production of electrons probably increases, the effect of which resembles that of the increased conductivity. The increased conductivity makes the current increase steeply in the final stage shortly before the cathode is reached. The first branch to reach the plate (often two at the same time, rarely more), connects both electrodes like a metallic conductor, and the main stroke takes place in this channel, which does not form tracks of its own, but uses the tracks of the branches. The parallel branches lagged in the process are visible on the picture as half-developed streamers; they cannot spark over the farther spacing with increased velocity and form an additional main stroke. This shows that the adjacent cathode and the main stroke cannot accelerate the development of the branches. The maximum current value developed at the main stroke does by no means characterize the discharge; it adjusts itself to the circuit constants, and the main stroke only produces additional resistance.

It may be of importance to future investigations that no channel growing in the opposite direction or other light phenomena from the lower plate (cathode) was observed. No negative discharge region is thus to be found in the gap. This applies also to the latest stage, when the branch has approached rather close to the cathode plate. The growth of the branches continues by the aid of the tuft mechanism, thus directed from the anode side. This seems to prove that the liberation of the secondary electrons at the impulse discharge is determined by the bundle alone, whereas the positive ions are not important to the liberation of the electrons (from the cathode) because of their low mobility.

d. Influence of the gap length on the mechanism.

For a sphere, the length (1_0) of the first phase at corona voltage remains practically the same at various gap lengths (Fig. 9) and may be considered constant. *At long gaps* the first phase does not cover the whole gap at corona voltage (point b, Fig. 7). Although the length of the crown increases with increasing voltage, it cannot cross the whole gap. The crown cannot reach the cathode even shortly before the breakdown voltage (point c, Fig. 7); a part of the gap is left without the crown of the first phase (Fig. 9). Hence the second phase in this case runs partly on the surface of the crown and partly has to cross the air by the aid of the bundle. The influence of the first phase appears from the voltage curve in the constant value ΔV (Fig. 2). The remaining voltage, which constitutes the main part of it, is used up for the covering of the bundle of the second phase. An important indication of the prevailing conditions is given by the values $dV/d\delta$ (Fig. 25) measured from the voltage curve (Fig. 1): at long gaps the slope remains the same for all gaps and spheres, i.e. 4.82 kV/cm. The cause of this phenomenon is probably to be found in the unchanged mechanism of the discharge. If this supposition is valid also for very long gaps, we thereby obtain the gradient value for the positive lightning stroke, which will make it possible to determine exactly the potential of the cloud if the distance is known. The small value ΔV may be neglected here—the average gradient assumes the value $dV/d\delta$ (cf. Fig. 22).

A change of the curve $dV/d\delta$ takes place with decreasing gap length at a certain critical value. The crown of the first phase begins to influence the development of the second phase. The decrease of the average gradient (Fig. 25) proves that the process of the second phase on the surface of the crown takes place with a smaller gradient than in the air. The gradient decreases with the gap length and reaches a minimum—between 1.6 and 2.4 kV/cm—at about the double length of the crown. If the gap length is lowered further, the gradient begins to rise; the increase is slow till a value corresponding to the length of the crown is reached, but at still shorter gaps it proceeds rapidly. The optimum condition for the development of the second phase, i.e. for the discharge also, is thus had at about the double length of the crown. Here a small increase of the gap length requires the minimum voltage increase: each cm requires about 2 kV/cm. Half the second phase develops on the surface of the crown, whereas the other half develops in the air, its development being the one best supported by the first phase.

When the crown of the first phase strikes the plate, i.e. the gap length is adjusted so as to correspond to the length of the crown, the critical gap length is had. Below this value the curves for corona voltage and for sparking voltage are not to be had separately: in the subsequent stage they form a common curve. The discharge progresses completely along the surface of the crown; once initiated, it cannot stop by itself.

Further decrease of the gap length causes a disturbance of the development of

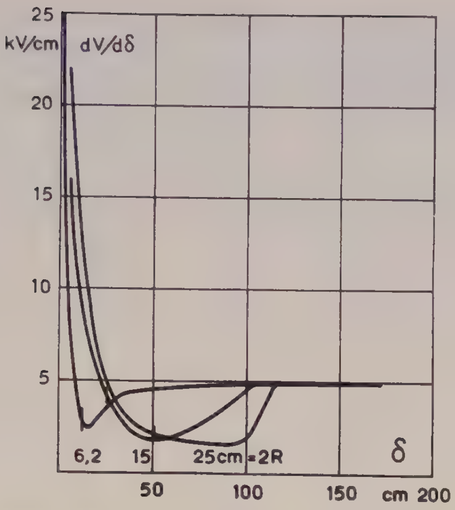

Fig. 25. dV/dδ values derived from the voltage characteristics (Fig. 1). The perpendicular streaks indicate the length of the crown, i.e. the limit, up to which the corona voltage and the sparking voltage coincide.

the first phase. The crown probably has no possibility of developing fully, or the electrons cannot reach their full velocity in the space at the same field condition. The voltage must be increased accordingly, and the curve dV/dδ rises steeply. At gap lengths down to $\delta = l_0$ (l_0 = crown length), the development occurs according to the mechanism described, i.e. by the aid of the first and second phases. From $\delta = l_0$ on, the mechanism is modified by degrees, as the two phases are no longer able to develop completely. The stem remains about the same, but the crown diminishes with decreased gap length, till finally the stem alone remains at the gap length $\delta = s$ (s = stem length). A general change of the mechanism takes place: the discharge develops only in the stem, and thereby the spark loses its ziz-zag form, being henceforth rectilinear. As the object of the present investigation was to explain the mechanism of spark discharge at long gaps, no particular attention was directed towards the region of short gaps, only a few preliminary photographs being taken. It seems likely that just this region is the one in which the development of the discharge can be explained satisfactorily with the hitherto prevalent conceptions of the streamer and Townsend theories.

e. Comparison with earlier investigations.

1. First the *average field strength* for the arrangement sphere-to-plane and long gaps measured at the sparking voltage will be compared with the values known from earlier investigations. Table 6 gives a survey of the measurements.

These data may be regarded as a certain corroboration of the validity of our results for other kinds of voltage as well. As the investigations were carried out with different methods, the accordance is satisfactory.

2. The forms of the pre-discharge given by the various authors partly differ considerably from ours, and they will therefore be discussed briefly. As mentioned,

Table 6.

The average sparking field for the arrangement sphere-to-plane and long gaps.

Authors	Kind of electrode	Diameter of electrode cm	Gap length cm	Applied voltage	Average field kV/cm
WEICKER (7)	Point	—	60	50 cps	4.62
	Sphere	5	56	»	4.87
PEEK (8)	Point	—	400	60 cps	4.25
TOEPLER (14)	Point	—	100	D.C.	4.90
GOODLET, EDWARDS, PERRY (20)	Point	—	150	60 cps	4.69
	Sphere	12.5	»	»	4.46
	Sphere	25	»	»	4.52
BELLASCHI, TEAGUE (9)	Point	—	150	60 cps	4.70
	Sphere	25	»	»	4.30
Authors' measurement	Point	—	150	Impulse 1/50	4.82
	Sphere	6.2	»	»	4.86
	Sphere	15	»	»	4.94
	Sphere	25	»	»	4.99

the development of the discharge depends on the ratio of the gap length to the length of the stem of the electrode in question. In the region of δ = length of the stem, the tracks of the pre-discharge and later also the spark are rectilinear, e.g. FLEGLER and RAETHER Fig. 7 in (21), RAETHER (2). At the gap lengths, at which the crown is shortened, the gap is mainly covered by the stem, only the lower part is left for the crown. The pre-discharge and the spark develop longer or shorter branches in the lower part. Such pictures are given by TERADA and NAKAYA (19), ALLIBONE and MEEK (12, Fig. 15), and probably Fig. 9 e of RAETHER (2) also belongs to this type of pre-discharge. At long gaps with completely developed first phase, the discharge figures are identical with ours. The following authors may be mentioned in this connection:

The first phase is photographed by TOROK (3), SLEPIAN and TOROK (4), KROEMER (22), NAKAYA and YAMASAKI (23), BRADLEY and SNODDY (24). The chopped second phase is given by HOLZER (5), MATTHIAS (25), and particularly exhaustively by ALLIBONE and MEEK (12).

3. Our observation that the second phase and spark develops first on the surface of the space charge is supported especially convincingly by HOWELL (26). Fig. 12 in (26) demonstrates unequivocally how the spark developing on the surface of the space charge spreads more and more together with the space charge with increasing pressure.

4. The discharge phenomenon observed by Toepler (27) and its development at great gap length between the point and the plate and gradual increase of the voltage is fully identical with the development of our second phase. The rays seen in Fig. 9 in (27) are designated bundles on our photographs. The supposition expressed by him, that also the formation of very long sparks or the growth of lightning strokes should present a certain likeness to gliding phenomena, must be said partly to be highly appropriate.

5. Although the Lichtenberg figures are not equal to the discharge phenomena presented in the present paper in all their stages, some details are so strikingly identical that similarities must be supposed to exist between the development of the gliding spark and the discharge in the air.

A comparison between our Fig. 11, v. Hippel's Fig. 6 (28) and Lord Armstrong's Fig. 12 (41) confirms this. The primary positive Lichtenberg figures are identical with the first phase. Only the stem is lacking in the Lichtenberg figures, which may be explained by the different arrangement of the electrodes. With the suitable arrangement and potential used by Lord Armstrong the unipolar figures have a lineal stream and a dispersive part [fig. 22 in (41)]. Simpson has also given an example of the positive Lichtenberg figures: two circular electrodes over the photographic plate are used instead of the usual one-point-electrode arrangement; the positive Lichtenberg figures are provided with a stem, as can be seen in Simpson's fig. 6 (29). In this case the identity is complete and further confirmed by the time of development, which in both cases is of the order of a few 10^{-8} sec.

The second phase of the discharge is identical with the figures of the gliding spark, as will be seen if our Fig. 14 is compared with Fig. 11 in (28). The spark on the photographic plate thus develops in a manner similar to the development of the discharge in the air.

But not only the Lichtenberg figures in air resemble sparks in the air. Also in various gases the Lichtenberg figures provide a possibility of distinguishing single details more clearly. In Fig. 9 and 25 in (30) the analogy of the mechanism of the propagation of the second phase is clearly visible: the single tufts at the ends are jumped over by a spark in one or several places, and the next tuft is formed at the end of the developed channel.

Fig. 19 in (30) gives a further corroboration of the tendency of the second phase to develop on the periphery of the discontinuity. On the picture the back figures, which are identical with the second phase, run along the outer edges of the negative primary figures.

An interesting detail, which has been established by the comparison between the Lichtenberg figures and our pictures, will finally be pointed out. As is well known (31), the Lichtenberg figures do not develop continuously, but in successive steps. The sector-like tufts are ranged close to each other by a straight spark crossing the tuft. At the spark-jumping a bend is almost invariably formed at the transit points; the path is thus made discontinuous and the direction of the channel changed abruptly at an angle of about 90°. E.g. Fig. 3 a in (31 b) and Fig. 13 in (30) show the negative Lichtenberg figures with this particularly conspicuous feature of the development. A detailed study of the process of the development of the second phase of the discharge in air yields a striking result: this phase also displays this discontinuity in its path. The bend point, which has been made more clearly visible above to the right in the Fig. 18 by an appropriate printing procedure, has quite the same character as in the Lichtenberg figures. Hence we are obliged to assume that the process of the development of the second phase and that of the negative Lichtenberg figures are determined by the same factors. As the identity of the second phase and the positive figures of the gliding space has been proved above, we thus arrive at the singular conclusion that the negative Lichtenberg figures and the positive figures of the gliding spark have factors of formation in common. The difference is probably to be found only in different length of the tuft.

6. The extensive research of Pedersen (39) will be mentioned in fuller detail. Many of his observations are highly similar to our phenomena.

The following properties of the *regular positive Lichtenberg figures* lead us to the conclusion that they are identical with the first phase of spark discharge:

a. Because of the duration of the development, of the order of 3.10^{-8} sec, pure positive spreaders are to be had only by a potential flash of very short duration (p. 8 and 42).

b. The photographic intensity of the filaments has very nearly the same value over the whole area of the spreaders (p. 21, 22 and plate 21, I, III), the innermost parts of the spreaders very often having much stronger intensity than the more removed parts; the intensity drops down very abruptly (p. 22 and plate 20 I). The strongly luminous part may be assumed to be identical with our stem.

c. Positive Lichtenberg figures do not start before the voltage has reached a certain minimum value, and the figures always have a finite and not inconsiderable range, which in the starting stage is nearly independent of the voltage (p. 28)—they thus behave similarly to our filament lengths at corona voltage (l_0 in Fig. 7).

d. The spherical electrode forms larger spreaders than the point-electrode (p. 34, 35), which is in accordance with Fig. 8.

e. The filaments have no conductivity worth mentioning (p. 45).

f. The figures may also appear successively with a time lag (p. 43). E.g. plate 17 presents no less than 4 single figures, developed in an interval $5.3 \cdot 10^{-8}$ sec; those developed later do not enter the region of those already developed, but develop on the non-occupied space.

g. Also externally the primary Lichtenberg figures resemble the figures of the first phase of the discharge in the present experiments.

The question whether the trunks always have a brighter part adjoining the electrode is answered in the negative by Pedersen. He assumes that this phenomenon is caused by the oscillations in the circuit and consequently are to be observed only if such oscillations are at hand. YOSHIDA (40), however, is of the opinion that every branch of the positive figures must consist of two parts: one more intense portion near the electrode and one weaker portion more removed. On the pictures of PEDERSEN, the part with strong intensity may be observed even in the onset stage of the development and at low pressure (plate 22 at 100 mm Hg). As the stem is invariably present during the first phase of the development in the present investigation and similar phenomena may also be observed at D. C. and 50-cycle A. C. corona (16), we cannot agree fully with the opinion of PEDERSEN without further extensive experiments.

Pedersen has also observed a process that may be considered analogous to the second phase of spark discharge. At sufficient duration of the voltage an irregular positive discharge develops, of a character altogether different from that of the primary Lichtenberg figures (p. 45). It has a somewhat blurred character and develops further in the *positive spark tracks*. A development that is identical with the starting of the second phase is clearly visible on the plate 20 II (cf. Fig. 12): the highly luminous tracks do not branch from the end of the stem, but from the middle part of the stem.

It is interesting to observe that: 1) The starting picture of the *negative discharge tracks* frequently conforms fully to the picture of the stem. The negative discharge tracks always develop in the centre of the sectors of the regular negative Lichtenberg figures (p. 43). The development of the negative discharge tracks reproduced on plate 27 IV is strikingly similar to the picture of the stem in our Fig. 4. Essentially the same process one can see in Lord Armstrong's fig. 21 (41).—2) The negative gliding spark very often jumps from one spreader to another, forming sharp bends in its path (p. 43 and plate 27 VI). Similar processes have been observed in the path of the second phase also in the present investigation (Fig. 18).

We will finally call attention to an interesting result of Pedersen's experiments: the formation and the process of the development of the primary Lichtenberg figures are independent of the additional ionization of the space. This has been proved for previously produced as well as for simultaneous artificial ionization (p. 60).

7. Extensive investigations have long since been carried out with positive corona with an arrangement of very fine point-to-plane. For the length of the streamer (identical with our crown length), KIP (32) has established, in accordance with us, the existence of an increase proportional to the diameter of the electrode. His values, however, differ greatly from ours: in Fig. 7 in (32) the length of the streamer at an electrode radius of 0.1 cm is 2 cm, as compared with the value 0.38 cm calculated by us. Nor does the length of the stem 0.17 cm and of the crown 0.3 cm (33, Fig. 9 b) given by LOEB for an electrode radius of 0.019 cm accord with the values 0.011 and 0.073 cm calculated by us. A close study of this would be desirable.

The above-mentioned work by LOEB (33) gives a highly characteristic picture of the corona—a stem with a crown. The latter is seen as a diffuse light phenomenon. The picture is probably a superposition of several consecutive discharges, and the filamentary structure of the single streamers has therefore been lost.

The current curve at the development of the corona has been studied by among others KIP (32), and recently by ENGLISH (34) by the aid of a very sensitive synchroscope. The time of the development has been found to be of the order of $2\text{–}3 \cdot 10^{-8}$sec. It will hence have to be assumed that the streamer in question is identical with our first phase. The duration of the first phase may be estimated at 0.5 μs. The current curve has a very steep front and a flat tail.

8. A brief comparison will finally be given between the pictures of breakdown in air and breakdown in liquids. STAACK's pictures of the gliding spark in oil present complete identity with our second phase, as is evident from a comparison of Fig. 16 in (36) with our Fig. 14. Further, as NIKURADSE (36) has pointed out, the general development of the current-voltage curve in purified dielectric fluids is similar to that of breakdown in air—cf. Fig. 1 in (28) with Fig. 1 in (36). This constitutes a further corroboration of the supposition expressed by MARX (37), that the fundamental process is quite the same in breakdown in gases and in liquids.

f. Concluding remarks.

The investigation described leads to the conclusion that the field is not the only factor starting the process of spark discharge at long gaps and high voltages and determining its development. The existence of several factors is to be assumed, which depend on other influences than the field as well and appear either successively or several simultaneously. The whole mechanism forms a complicated process, and our knowledge of the various factors is insufficient as yet. The application of the Townsend and streamer theories involves considerable difficulties for long gaps. The opinion expressed by LOEB and KIP (38), that one criterion for spark breakdown cannot be and should never have been universally applied to all conditions, must be said to be highly appropriate for long gaps.

The first phase develops with the help of the electronic movement. The necessary velocity is produced partly by the field directly and partly by the stem by its part with cumulative ionization. Besides by the field, the condition of the start is also influenced by the presence of electrons in the air and their state. Although the distribution of the ions in the air is one of the most important initial factors, our knowledge of the source of the initiating electrons is still rather unsatisfactory. We believe that the main source of the necessary electrons is constituted by the radioactive substances in the air. Not until it becomes possible to determine the exact distribution of the ions in the air during the experiments can we expect from the various investigators results that accord better mutually and can be reproduced. It is customary nowadays to aim at such results by the aid of radioactive substances. Unfortunately, however, the natural property and density of the ions in the air is then lost, and therefore the results should be applied to the natural air with the greatest caution.

The development of the first phase alone is no guarantee for the further development of the discharge, which also requires a certain gap length in proportion to the length of the crown. If the gap length exceeds a critical value, the first phase remains the only phenomenon of the discharge. It should also be mentioned that it was not possible to find in the first phase an indication of the influence of photoionization.

Two components of the first phase are important to the origin of the second phase—the stem and the surface of the space charge. The plasma channel of the second phase starts growing in the part of the stem with cumulative ionization, and for the further process the best conditions are offered by the surface of the space charge. The development of the second phase probably takes place with the help of photoionization. The two different forms of the phenomenon are not clear, however. The first one, which develops in successive steps by short tufts at the end of the branches, causes the increase of the branches. The second phenomenon, which we have given the name "bundle," can develop far with the voltage, so as to cover the whole gap down to the lower plate. The bundle is to be regarded as a source of electrons, producing the electrons in the air (seemingly also in the region of the space charge of the first phase) necessary to the continuation of the development.

If the bundle is unable to traverse the whole gap because of insufficient voltage, the second phase remains half developed, the branches being visible only in the upper part, and no breakdown occurs. There are various names for such half-developed discharges; thus e.g. corona designates a discharge constituted by the first phase alone or with insignificant branches of the second phase. Unfortunately there is no universally adopted international word for discharges with better developed branches of the second phase. In English they are called *brush discharge*. In the German literature (14) the following names are found: *Büschel*, *Büschelband*, *Büschelbogen*, *Streifenentladung*, etc.

The third and last phase—the main stroke—utilizes for its progress the first branch that reaches the plate; no channel growing from the plate towards the branch is visible. The discharge progresses solely with the help of the branches of the second phase; with our electrode arrangement (point-to-plane or sphere-to-plane) the electrode spacing is covered by the positive discharge region alone.

Already Toepler (27) found that the breakdown in the air is to some extent analogous to that of the gliding discharge. Instead of the extension by spots on the plate, a somewhat similar extension on the surface of the space charge is had (the crown of the first phase). Accordingly the proportion of the dimensions to the gap length is of decisive importance for the determination of the kind of the mechanism of the discharge. With appropriate adjustment a breakdown in air occurs almost in the same manner as a gliding spark on the surface of a plate. The progress of the pre-discharge in its various stages is much more difficult to observe at the breakdown in air than at a gliding discharge. This gives rise to the supposition that the various partial processes can be explained in their details with greater ease by the aid of the gliding discharge than if direct observation of the breakdown in air were possible. At any rate it is to be expected that a complete picture of the complicated mechanism of discharge in air, controlled by many factors, will be more easily obtained in this way.

SUMMARY

Photographs of the suppressed discharge make it possible to follow the development of the spark in the air. Experiments have been carried on only with the arrangements sphere-to-plane and point-to-plane, positive polarity and long gaps, and with non-uniform fields. A variant of the mechanism of the discharge was proposed.

A discharge consists of three major parts (phases). The first phase, for spheres constituted by a short stem and a long crown, appears suddenly at the corona voltage and is caused by electronic motion. The time of the development is of the order of a few 10^{-8} sec. As the given fields are weak, the presence of initiatory electrons in the air should be considered a fact. The source of the electrons should be looked for in the radioactive substances in the air. The length of the crown determines the kind of the mechanism and the sparking voltage. The second phase follows immediately upon the first phase. It probably develops with the help of photoionization, first on the surface of the crown of the first phase. The branches grow in steps by the aid of small tufts at their ends. Furthermore a luminous bundle of rays develops, the length of which increases with the voltage and traverses the whole gap at sparking voltage. The bundle provides the production of the electrons necessary to the increase of the branches. The third phase—the main stroke—does not appear till a branch has crossed the whole gap and reached the lower plate. The main stroke runs through this branch (sometimes through two branches simultaneously). No channel growing forth from the plate towards the main stroke was observed. Here the progress of the discharge is determined by the anode. The current begins to increase already during the second phase; the curve of the current is particularly steep before the main stroke and reaches its definite maximal value, determined by the constants of the circuit, at the main stroke.

It can be proved that the Lichtenberg figures and the gliding discharge are analogous in single parts to the discharge in air. Accordingly a breakdown in air may be regarded as being constituted partly by gliding phenomena. Also the gliding discharge in purified liquids resembles the breakdown in air.

The breakdown in air is a complicated phenomenon controlled by many factors. Although these factors mainly depend on the field, also other influences are probably at hand. The application of the Townsend and streamer theories involves considerable difficulties for long gaps. It is probably impossible to establish one criterion for spark breakdown universally applicable to all conditions.

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Contents

1. Introduction........ 347
2. Apparatus and Technique........ 348
3. Potential Curves for the Arrangement Sphere-to-Plane........ 348
4. Photographs of Spark Discharge........ 351
    a. General description........ 351
    b. First phase of spark discharge........ 351
    c. Second phase of spark discharge........ 360
    d. Third phase of spark discharge........ 360
5. Discussion........ 369
    a. Calculation of the field........ 369
    b. The starting-point of ionization by collision in the space........ 371
    c. The mechanism of spark discharge sphere-to-plane with long gaps... 372
    d. Influence of the gap length on the mechanism........ 376
    e. Comparison with earlier investigations........ 377
    f. Concluding remarks........ 381
Summary........ 383

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